DISCUSSION BEFORE THE RADIO SECTION, 4TH DECEMBER, 1946.

Dr. R. L. Smith-Rose: Perhaps the few rather general remarks which I have to make may pave the way for the comments of speakers who are more versed in this subject and more competent to discuss, and possibly to criticize, this paper than I. I feel that we have heard a paper which, in the annals of The Institution, will be regarded as something of a classic in years to come. I have been listening to the author this evening with great respect for the manner in which, in less than half an hour, he has presented to us a paper containing over 260 mathematical equations and much original thought.

It is perhaps significant that the author comes from the Cavendish Laboratory—though he has told us that this paper was written whilst he was serving temporarily in a Government establishment—because the paper does in reality carry on the work begun by Clerk Maxwell in which he deduced that when an electric current flowing in a circuit is made to vary, there is a certain amount of radiation from the circuit. This radiation was identified at the time with light, but we have since come to realize that it forms the basis of the whole of the radio-frequency spectrum as we know it to-day.

I think that this paper is of very great value and help to the Radio Section, but it will also be of assistance, though it will possibly present some difficulty, to the rest of the membership of The Institution, because one of the commonest experiences that we have when we meet ordinary power engineers, who are not familiar with radio technique, is to find that they have great difficulty in understanding how the electric energy, which they thought was nicely confined in the cables which they lay down to steer it from one place to another, ever gets away from a circuit. Here we have the author telling us that by a simple extension of our ideas of circuits and circuit analysis that difficulty is removed, though I still feel that some members of The Institution may have difficulty in grasping the idea of free space having an intrinsic resistance; and when we actually give a value of 377 ohms to that resistance I think they will be a little amazed in trying to understand the procedure which has led to this conclusion.

Looking back at the history of the subject, I think we shall find that Maxwell was very close to taking this step, because it does follow from his work in this subject of electricity and magnetism that when we speak of circuits and of sending electric current along wires the electric energy is not really confined to the wire; it is actually travelling in the space surrounding the wire. Maxwell was the first to grasp that idea, and from that to the process of detaching the energy from the wire is a relatively simple step, though it has taken us many years to achieve; and it is this step which the author has now explained to us.

Mr. J. A. Ratcliffe: Dr. Booker's paper is, in the true sense, an "integrating" paper which shows the relation between different branches of knowledge. I feel sure that this paper will become a classic, particularly in the teaching of this subject.

Because I think the ideas of the paper will be widely used in teaching I am sorry the author has made it look as though the ideas of "wave impedance" were related to the particular system of units employed. The ideas of wave impedance are quite fundamental and in no way related to any special set of units. It is true that the numbers involved come out a little more simply if any rationalized system is used, but that is a matter of convenience only and does not alter the value of the wave impedance concept even when unrationalized systems are used.

I also deprecate, particularly for teaching purposes, the mention of any special units after a purely algebraic expression, which ought to retain its validity whatever the units. We do not write "$E = \frac{1}{2}mv^2$ joules," or "$F = ma$ newtons," because these two equations are equally true if energy is measured in ergs or ft-poundals, and force in dynes, poundals or indeed any other set of consistent units. Why then do we have to write "$W = \frac{1}{2}CV^2$ joules" (eqn. 233) as though this valuable equation were not true for any other set of units?

In equation (78) mention is made of an important frequency equal to σ/κ, at which the electrical properties of the ground change over from conducting to dielectric. It is of interest to note that the reciprocal of this frequency is the "relaxation" time of the medium, in the sense that the charge on a condenser having the medium as a conducting dielectric would leak away with this time constant.

It is interesting to note from the left-hand column of Fig. 8 that, under certain conditions, the Brewster angle phenomenon may be in evidence even when the wave is polarized with its electric vector parallel to the boundary. Can the author explain these conditions a little more fully?

The curves of Figs. 7 and 8 have presumably been plotted with reference to some particular values of constants characterizing the medium. It would be of value to have these constants marked on the graphs.

I find the terms "intrinsic-," "surface-" and "field-" impedance somewhat confusing in a first reading of the paper, and I should like to see a short definition of all three added.

Dr. G. G. MacFarlane: There is one aspect of the conception of field impedance which I should like to emphasize. It was touched on by the author in his introductory remarks and is mentioned at the end of the paper. It concerns the great simplification which is introduced into our thinking processes when we are considering junctions of transmission-line systems, and for that matter of waveguides, because this field impedance enables us to write down equivalent circuits made up of lines and lumped circuit elements. One of the examples given in the paper illustrates this: it is that of the wire grid, where it is shown that when a plane wave is incident normally on a wire grid and the electric field is vibrating parallel to the length of the wires, the field on both sides of the grid can be calculated in the same way as one would calculate the currents and voltages on the two sides of a transmission line in which there is a coil and the inductive field of that coil is analagous to the inductive field which the plane wave produces around the grid.

The point that I want to bring out here, however, is the fact that this conception is limited, and the limitations from the point of view of engineering are limitations of which one must never lose sight. Suppose that we have a parallel-strip transmission-line, rather like Fig. 1, and that that line joins on to a second line of the same type, but in which the spacing between the strips is increased fourfold, so that on the one side we have a spacing of a and on the other side of $4a$. The equivalent circuit for that system is two transmission lines of which, if we maintain the idea of field impedance, each has the same characteristic impedance. That seems a little odd at first, because normally the spacing between the strips comes into the impedance, in our normal definitions of characteristic impedance. However, we want to maintain the idea of wave impedance, and so we introduce a transformer between the lines whose turns ratio is 2 : 1, giving an impedance ratio of 4 : 1, but at that junction there is also a small capacitance due to the disturbance caused at the junction.

That is quite a good representation, and the analogy is close if one condition is satisfied, namely that the wavelength is very long compared with the larger spacing in the two lines, i.e. $4a$. Let us see what happens when the wavelength is decreased. If we decrease the wavelength so that the width between the wider line ($4a$) becomes just a little less than half a wavelength, we find that this capacitance which we have to introduce at the junction,

and which was small, has suddenly become very large. The reason for this, as mentioned in the paper for other cases, is that an evanescent wave has popped up which is spreading for a considerable distance from the junction along the wider transmission. This is where the analogy between the field system and the simple transmission line seems to break down. We see that this capacitance is now varying as we change the wavelength, which a normal capacitance, such as a parallel-plate condenser, does not do. Secondly, in order to include in our equivalent circuit the entire capacitive field at this junction we must take our terminals so far away that this capacitive field has died away. That is the second serious limitation. The conception of field impedance, therefore, is extremely important in enabling us to obtain equivalent circuits for complicated field configurations such as junctions, but it is limited, and we must not lose sight of that fact.

Another point is that in the equivalent circuits which we obtain it is found necessary to include perfect transformers. By doing that we can ensure that there is an impedance match all the way along the system. Furthermore, if the system is one where, at a junction for instance, higher-order waves are produced which themselves travel, we can introduce these as transmission lines in parallel, each with its own transformer.

Mr. G. Millington: The paper will be of great use to engineers who are familiar with the impedance concept in circuit theory. There is, however, a danger of putting the emphasis the wrong way round, and of leading the engineer to believe that the circuit theory is fundamental, and that Maxwell's equations can be replaced by it. It is Maxwell's equations that are fundamental, and they are needed to give a rigid treatment of transmission line theory. The simple line theory when applied to aerial systems gives a good first approximation, but, as the author himself has shown in one of his war-time reports, the complete theory, though much more difficult, is needed to give a true understanding of their behaviour.

With regard to the possible limitations of the paper, I feel that a little more emphasis should have been laid earlier in the paper on the fact that it deals very largely with plane waves. I should like to know whether the treatment of a rectangular waveguide in terms of two sets of criss-cross plane waves has any application to circular guides. Moreover, with this treatment one is apt to lose sight of the fact that one of the most difficult parts of the problem is the fitting of the plane wave solution to the source.

Another case where I should find the impedance concept difficult to use is that of a wave incident on a doubly-refracting medium such as the ionosphere in the presence of the earth's magnetic field. I should much prefer to approach the problem directly in terms of Maxwell's equations. In ground-wave propagation also, where $\mathscr{E}$ and H are not necessarily in phase or mutually at right angles and transverse to the direction of propagation, the impedance concept would appear to be less simple. I should like to ask the author whether the impedance concept can be conveniently adapted to deal with these more complicated situations.

It is interesting to note that if the problem of a plane wave incident on a medium of different refractive index is tackled by converting the second-order wave equation into a first-order non-linear equation of the Riccati type, the function one deals with is the ratio of the electric and magnetic fields in the wave, and is thus an impedance as defined by the author. This method of studying the reflection problem is very useful, especially for media in which the refractive index is a function of the distance from the boundary.

In conclusion, while raising these points about the possible limitations to the impedance concept, I should like to say that I appreciate its extreme value in the hands of an expert like the author, who has turned it to such good account in his work on the slot aerial.

Dr. H. P. Williams: Mr. Ratcliffe has pointed out that the impedance concept does not necessarily involve the use of the M.K.S. system, but I think that they do go very well together. In particular it is appropriate to use this system in a paper intended for electrical engineers.

As an example of the easy way in which the impedance concept can provide a solution, let us imagine that we have a radio altimeter operating over a layer of ice with sea water underneath. When the ice is not new it is relatively free of salt, and hence there might be a certain thickness of ice and some particular wavelength for which complete absorption would take place. It so happens that the decrease in the permittivity of ice at ultra-high frequencies prevents a matching condition being achieved, with the result that the reflection coefficient is always at least 0·5. But to illustrate the method, let us imagine that the permittivity is 80 in each case; then the intrinsic impedance of ice would be 42 ohms, while that of the sea water would be $15{\cdot}4\lambda^{-\frac{1}{2}}(1+j)$ ohms for wavelengths above 1 m. With the aid of a transmission-line diagram it is very simple to discover that an impedance match would be obtained if λ were equal to 9 m and if the thickness of the ice were 2 m.

I should also like to say that a very useful parameter is the complex permittivity, which is given in a neat form in the M.K.S. system, namely $\kappa' = \kappa_r - j60\lambda\sigma$, where κ_r = relative permittivity, λ = wavelength in metres, and σ = conductivity in mhos/m.

Typical values for σ are 5 for sea water, 0·01 for a moderately well conducting earth and 0·001 for a bad earth; consequently a simple mental calculation will give the complex permittivity. The use of this expression gives the following convenient form for the intrinsic impedance of a medium [eqn. (52*b*) in the author's paper]:

$$Z = 377\sqrt{\frac{\mu_r}{\kappa_r - j60\lambda\sigma}}$$

where μ_r is the relative permeability of the medium.

It is instructive to regard the Brewster angle as the consequence of a struggle between two rival boundary conditions. For example, with a fairly good conductiing earth the electric intensity tends to be annihilated in the ground; hence, with an incident wave which is normal to the surface, there must be a reflected wave whose electric vector is in opposition to that of the incident wave. In this way we satisfy the continuity of the tangential component. The other boundary condition which has to be satisfied is that of the continuity of the normal electric intensity; with normal incidence this is automatically satisfied since the normal intensity is zero. However, as the angle to the normal is increased (the polarization being vertical) we eventually reach a state when there is an appreciable normal component in the upper medium. This is contrary to the stipulation of only a small electric intensity in the medium, and therefore the two boundary conditions find themselves in opposition. The solution lies in having a much diminished reflected wave, most of the energy being dissipated in the ground.

I like the author's explanation of waveguide propagation. The more common viewpoint is to consider two waves which suffer successive reflections from the boundaries, but an even better picture is obtained by considering two plane waves crossing each other at an angle. The latter picture can be obtained very simply with water waves on a large pond. By simultaneously throwing in two large stones about 15 ft apart, we obtain a wave pattern in which the loci of the nodal points are hyperbolae, and these loci satisfy the boundary conditions of zero displacement (analogous to zero electric intensity.) The central channel is fairly straight and gives an excellent analogy of waveguide propagation.